Thickness and waviness of surface coatings formed by overlap: modelling and experiment

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Abstract

Several surface engineering techniques are known that form a hard facing coating on an inexpensive substrate by a successive overlap of individual cladding tracks. Typical examples include laser cladding and laser additive manufacturing. Realistic predicting the final thickness and waviness of the coating as a function of geometry of single cladding track and their overlap are lacking in literature. In this contribution a recursive model for the calculation of the coating profile is presented. A few basic shapes of single tracks are presumed and on the basis of physical assumptions a recursive formula is deduced to construct a shape of the whole coating profile. Calculations of such profiles for different shapes of tracks and different overlaps show a dependence of the coating thickness and its waviness on these parameters. The model is tested experimentally for a laser cladding process, in which the laser track is formed by a continuous deposition of small metallic particles into the meltpool formed by a high power laser beam continuously moving over the substrate.
Keywords: surface coatings, overlap, thick coatings, laser cladding.

1 Introduction

Formation of surfaces with good functional properties such as high hardness, high wear and corrosion resistance is a principal objective of surface engineering. A number of techniques are available that use different physical and technological processes towards this goals. Some of these techniques, which are producing thick coatings (~ 1mm), such as surface welding or cladding, are limited in lateral dimensions and overlap of individual tracks is necessary to cover a wider region. A typical example is the laser cladding process, in which a

WIT Transactions on Engineering Sciences, Vol 78,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/SECM130111

high power laser beam scans the substrate surface creating a meltpool, in which an additional material is fed in the form of metallic powder. Rapid solidification in an area behind the beam forms a few mm wide laser track in a single scan. Side overlap of such laser tracks results in wider coatings.

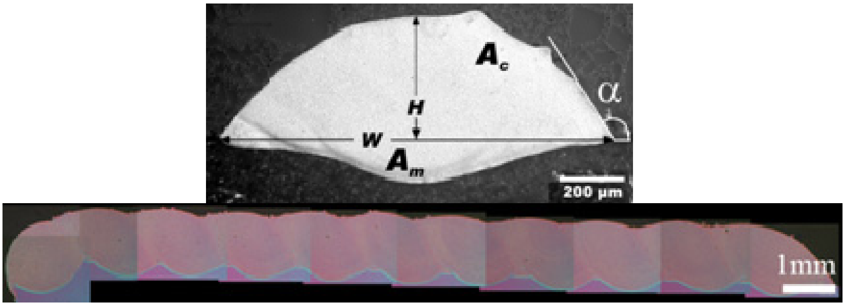

Figure 1: Transversal cross-section of single laser track (top) and laser clad coating (bottom), formed by 33% overlap.

Figure 1 shows a transversal cross-section of single cladding track prepared by laser cladding. Principal geometrical characteristics are described: width of a track *w*, height *H*, clad area A_c and melted area A_{m}. Lower part of Figure 1shows an example of laser clad tool steel coating formed by 33.3% overlap of individual laser tracks. The most common functions present in the literature describing the section profile of a single welding and laser cladding tracks are parabolic or circular arc segments [1–7]. It was observed experimentally that the parabolic profile is more realistic for tracks with a high *H/w* ratio, whilst the circle segment fits the track profile better when the ratio is smaller [1, 8]. There were, however, only a few attempts in the literature, in an attempt to model the shape of the coating profile based on the shape of single clad track. Li and Ma [1] proposed very simple additive model, in which the final coating profile is modelled as a summation of displaced single tracks. The main disadvantage of this model is an unphysical waviness that appears for some values of overlap ratio (see Fig. 2). Recent model of Suryakumar *et al*. [5] is based on some geometrical assumptions, when the valley between two track neighbours is filled using a circular shape of the same area as that of an overlapped area. This model eliminates the limitations of a previous one, but still fails to predict some of the experimentally observed features, such as a shift of the maximal point towards the previous track.

In present work we present a relatively simple overlap model based on basic physical assumptions. The model assumes an arbitrary shape of the single laser track described by three parametric functions $F_1(x)$. Profile of the whole coating is then modelled as sum of recursively calculated functions. The model may be used for estimation of final coating thickness and waviness from three starting parameters: track width *w*, track height *H* and overlap ratio *OR*.

2 Recursive overlap model

In formulation of our model for overlap of cladding tracks we suppose the following:

- The width of the track is controlled by a dimension of the energy source (in case of laser cladding by the width of laser beam) and stays constant during the process;
- The character of the track shape is controlled by a few physical factors such as viscosity of the melt, surface energy of the melt, gravitational force, etc. and it is not changed by overlap;
- Amount of the clad material is constant during successive cladding tracks.

The model is designed from these basic assumptions, which is explained in Fig. 2. The width of a single track *w* is defined by the distance between points A_1 and B_1. The profile of the first track is defined by a known function F_1. A hypothetical position of the second 'shifted' laser track with the same profile as F_1 is marked by a dashed profile between points A_2 and B_2. Overlap factor *OR* is defined as the distance between points A_2 and B_1 divided by the track width *w*.

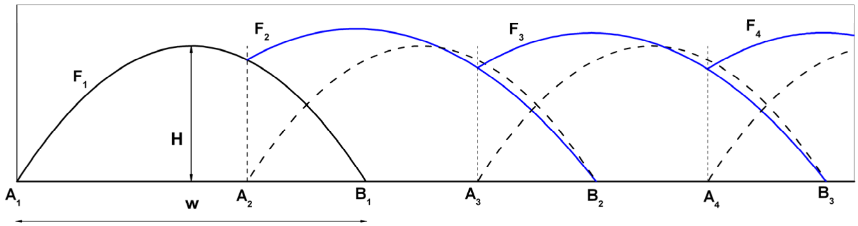

Figure 2: Model to calculate profile of coating formed by overlap of successive cladding tracks.

Profile of the second overlapped track F_2 has to be found on the base of function F_1 and physical assumptions made above and similarly all other profiles recursively on the base of previous one.

Mathematically we may formulate this model as follows: let *w* be the width of the single track, *H* its height and the points which define position of the first track are: $A_1 = 0$ and $B_1 = w$. Known function F_1 is integrable over an interval (A_1,B_1) and this function is zero outside of this interval. Let $z=(1-OR)$. The points at the start and at the end of *n*-th track are: $A_n=wz(n-1)$, $B_n=w+wz(n-1)$, $n= 1, 2 \ldots$ Profile of F_n starts on previous profile F_{n-1} at point A_n:

$$F_n(A_n) = F_{n-1}(A_n), \tag{0.1}$$

profile of F_n finishes in zero at point B_n:

$$F_n(B_n) = 0, \tag{0.2}$$

and finally the amount of the new material added in n-th track is the same as in the first one. Therefore:

$$\int_{A_n}^{B_n} F_n \, dx = \int_{A_1}^{B_1} F_1 \, dx + \int_{A_n}^{B_{n-1}} F_{n-1} \, dx \qquad (0.3)$$

Equations (1.1)–(1.3) are sufficient to solve such model when functions F_i are functions of the same type determined by 3 parameters. Parabolic functions $F_n=a_nx^2+b_nx+c_n$, $F_n=0$ for $x\notin(A_n,B_n)$ are a typical example. If parabolic functions are assumed in this model than: $a_1 = -4h/w^2$, $b_1 = 4h/w$ and $c_1 = 0$. All subsequent functions F_i that define coating profile between A_i and B_i, $i = 2,3 \ldots$ may be recursively calculated using above assumptions and equations.

3 Results of modelling

3.1 Parabolic profile shape

A parabolic shape of a single track is quite often proposed for different cladding techniques, including laser cladding. Figure 3 shows the results of the coating shape modelled in the case when the parabolic shape of the first track was selected with height to width ratio: $h/w=0.2$ for different overlap ratios.

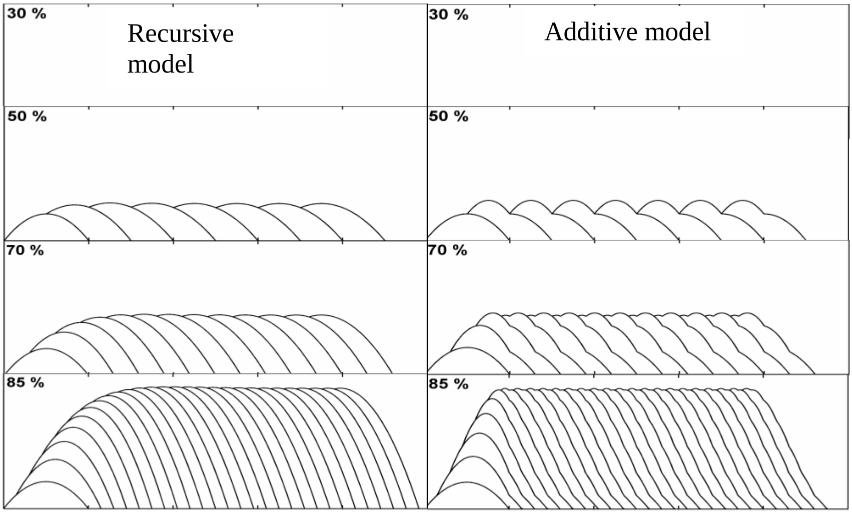

Figure 3: Recursively modelled profiles of the coating based on the parabolic shape of a single track calculated for different *OR* (left). Profiles with the same ORs modelled by the simple additive model proposed by Li and Ma [1] (right).

Figure 3 also shows the comparison with profiles modelled by a simple additive model [1] which generates some non-realistic waviness on the coating surface. Figure 4 shows the dependence of the coating surface waviness as a function of overlap ratio for both of these models. The relative waviness is defined as a difference between maximal and minimal points on the coating profile divided by the coating thickness taken at its profile maximum.

Figure 4 clearly demonstrates that in both models the relative waviness decreases with increasing overlap. While this decrease is smooth and monotonous in the Recursive model, the oscillations of waviness between two dashed lines are characteristic for the Additive model.

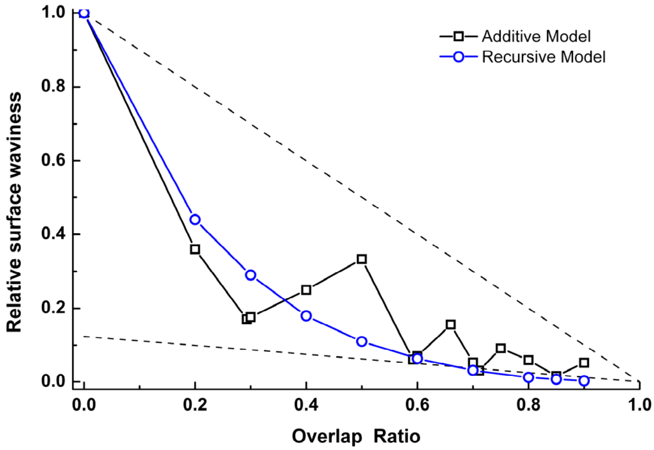

Figure 4: Relative surface waviness calculated for different overlap using Additive [1] and Recursive models.

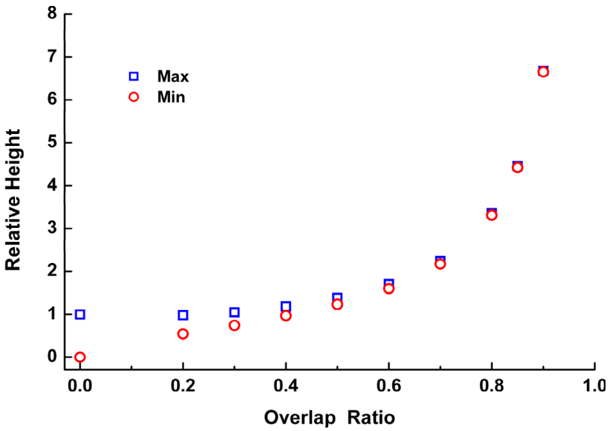

Figure 5: Dependence of the relative coating height in its maximal and minimal profile points.

Figure 5 shows the dependence of thickness of modelled coating as a function of overlap ratio. It is interesting to note that the effective coating thickness

(thickness after machining away the surface waviness) will be larger than the height of a single track only when the overlap exceeds 40 %. Overlap of 67.5 % is required to achieve a double effective thickness in comparison with the height of a single track.

3.2 Circular profile shape

The algebraic form of the circular arc can be generally expressed as:

$$(x-a)^2 + (y-b)^2 = R^2, \tag{0.4}$$

where R is the radius of the circle and a and b are x and y coordinate of the circle centre, respectively. In the case when the first arc profile intersects x axis in 0 and w, and the height of the arc is H, then $a_1=w/2$, $b_1=H-R_1$ and $R_1=(H^2+w^2/4)/2H$. Figure 6 shows results of calculations of coating profile based on circular arc profile of a single track. Starting ratio of H/w is 0.14

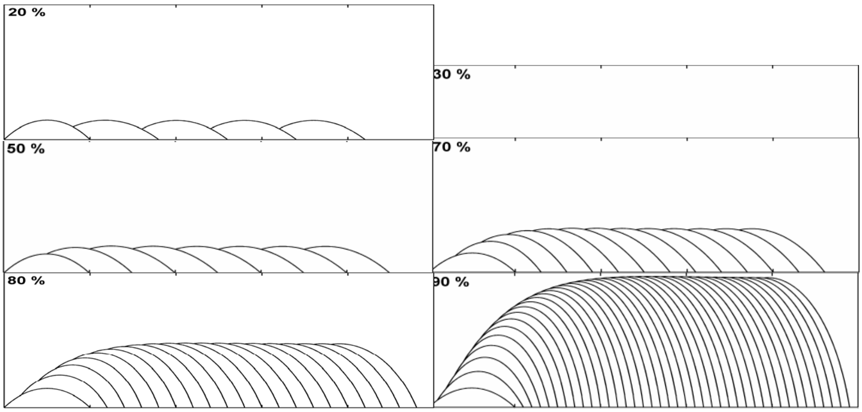

Figure 6: Recursively calculated profile of the coatings based on the circular shape of a single track for different overlap ratio.

There are very small differences in relative coating height and relative surface waviness between Parabolic and Circular models. Figure 7 shows these differences in relative heights for both models as a function of a variable *1/(1-OR)*, which linearized the dependence for overlap ratio *OR* larger than 0.5.

4 Comparison with experiment and discussion

To prove the validity of the Recursive model we executed laser cladding experiments in which the overlap ratio was gradually changed. Stainless steel 304 bar with diameter of 40 mm has been used as a substrate and stainless steel powder Höganäs 3533-00, specially developed for laser cladding technology, has been clad. Laser cladding with powder injection was realized to produce single-track and multiple-track (approx.14 mm wide) deposits with overlap ratios close to 0.2, 0.4, 0.5, 0.6 and 0.8 using cladding speed of 5 mm/s. Continuous wave

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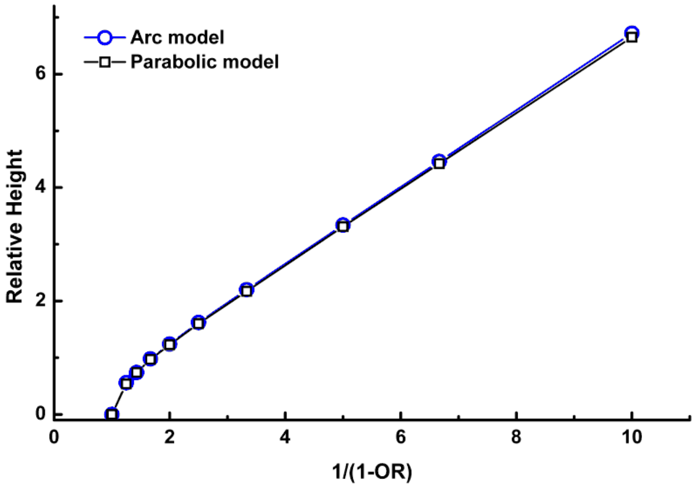

Figure 7: Relative height of the coating calculated for Circular and Parabolic arc profiles.

IPG fiber laser with a wavelength of 1.07 µm and laser power of 1000 W was used during deposition together with feeding system consisted of Metco Twin 10C powder feeder, argon as carrier and shielding gas and a side cladding nozzle.

Defocusing of the laser beam was tuned to obtain single laser track width of slightly more than 3 mm. Powder feeding rate was selected to achieve *H/w* ratio from interval 0.2-0.3. Exact width and height of the single laser track was measured on the single-track deposit made just shortly before the multiple-track deposit for each overlap ratio.

Figure 8 compares the experimentally obtained values of relative coating heights with the values obtained by recursive modelling using the parabolic shape of single laser track. It is clear that the height of the coating is predicted by recursive model reasonably well for overlap ratios smaller than 0.6. Hyperbolic increase of coating height with increasing of *OR* predicted in Fig. 5 is not observed experimentally. This is likely due to the substantial decrease of powder catchment efficiency on a high slope of previous laser track. An implementation of a new parameter in our Recursive model can be used to describe the efficiency factor as a function of profile slope. This implementation can be achieved by a modification of eq. 1.3. Further experimental data is required in order to implement this into the model.

Figure 9 demonstrates that the relative surface waviness is described by the model in a good accordance with experimental data over the whole range of experimentally used *OR*s. The Recursive model, however, slightly overestimates the experimentally observed relative surface waviness in OR interval from 0.2 to 0.5.

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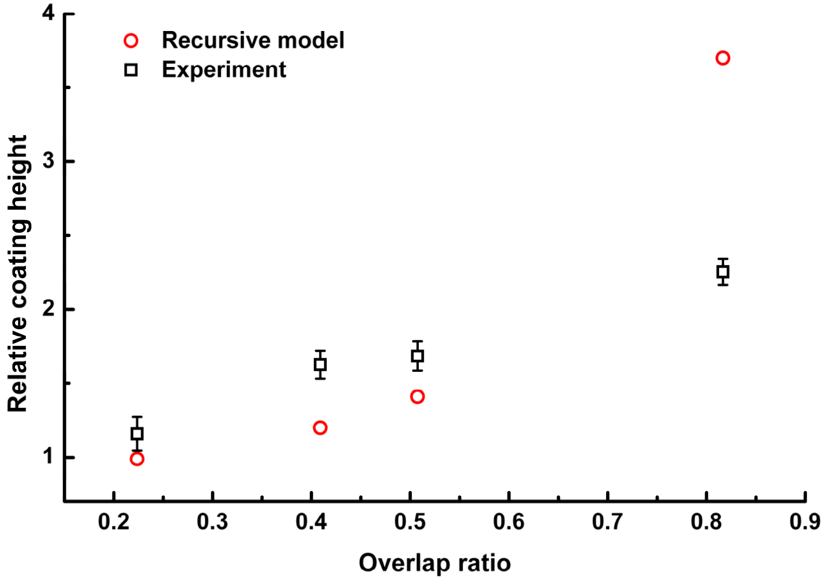

Figure 8: Comparison of experimental and calculated heights of the laser clad coatings for different ORs.

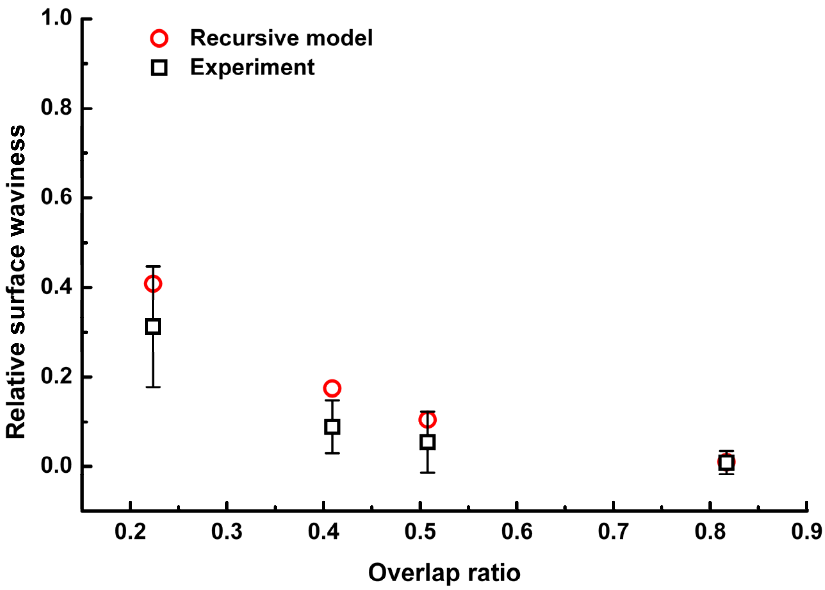

Figure 9: Comparison of experimental and calculated coating surface waviness for different ORs.

Recursive modelling of overlapped cladding profiles always results after few steps in a track profile, which has the stable shape and it is only shifted in a direction from the previous one. This fact allows a modelling of multi-layer structures with the same approach used in our work, with the flat substrate used in this model replaced by a wavy one, created by a shifting of stable type of function *F*.

5 Conclusions

This study presents a simple but physically sound model of the cladding tracks overlap process. Profile of the coating is calculated recursively for each overlapped track on the base of physically realistic assumptions that characterize the track size, track profile function and the amount of the clad material. Any kind of single track profile function which has three independent parameters may be selected to describe the shape of a track profile.

Calculated thickness of the coating prepared by overlap of laser cladding tracks are in a good agreement with the experimentally obtained values for overlap which does not exceed 50%. This model predicts the surface waviness of the coating quite well in a wide interval of the overlap ratio.

Acknowledgement

This research was carried out under project number M41.7.12463 in the framework of the Research Program of the Materials innovation institute, M2i (www.m2i.nl).

References

[1] Y. Li and J. Ma, “Study on overlapping in the laser cladding process,” Surface and Coatings Technology, vol. 90, no. 1, pp. 1–5, 1997.
[2] W. Aiyiti, W. Zhao, B. Lu, and Y. Tang, “Investigation of the overlapping parameters of MPAW-based rapid prototyping,” Rapid Prototyping Journal, vol. 12, no. 3, pp. 165–172, 2006.
[3] B. Chan, J. Pacey, and M. Bibby, “Modelling gas metal arc weld geometry using artificial neural network technology,” Can. Metall. Q., vol. 38, no. 1, pp. 43–51, Jan. 1999.
[4] Y. Cao, S. Zhu, X. Liang, and W. Wang, “Overlapping model of beads and curve fitting of bead section for rapid manufacturing by robotic MAG welding process,” Robotics and Computer-Integrated Manufacturing, vol. 27, no. 3, pp. 641–645, 2011.
[5] S. Suryakumar, K. P. Karunakaran, A. Bernard, U. Chandrasekhar, N. Raghavender, and D. Sharma, “Weld bead modeling and process optimization in Hybrid Layered Manufacturing,” Computer-Aided Design, vol. 43, no. 4, pp. 331–344, Apr. 2011.

[6] U. de Oliveira, V. Ocelík, and J. T. M. De Hosson, “Analysis of coaxial laser cladding processing conditions,” Surface and Coatings Technology, vol. 197, no. 2–3, pp. 127–136, Jul. 2005.
[7] L. Costa, I. Felde, T. Reti, Z. Kalazi, R. Colaco, R. Vilar, and B. Vero, “A simplified semi-empirical method to select the processing parameters for laser clad coatings,” in Materials Science, Testing and Informatics, vol. 414–4, J. Gyulai, Ed. Stafa-Zurich: Trans Tech Publications Ltd, 2003, pp. 385–393.
[8] J. Xiong, G. Zhang, H. Gao, and L. Wu, “Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing,” Robotics and Computer-Integrated Manufacturing, vol. 29, no. 2, pp. 417–423, Apr. 2013.